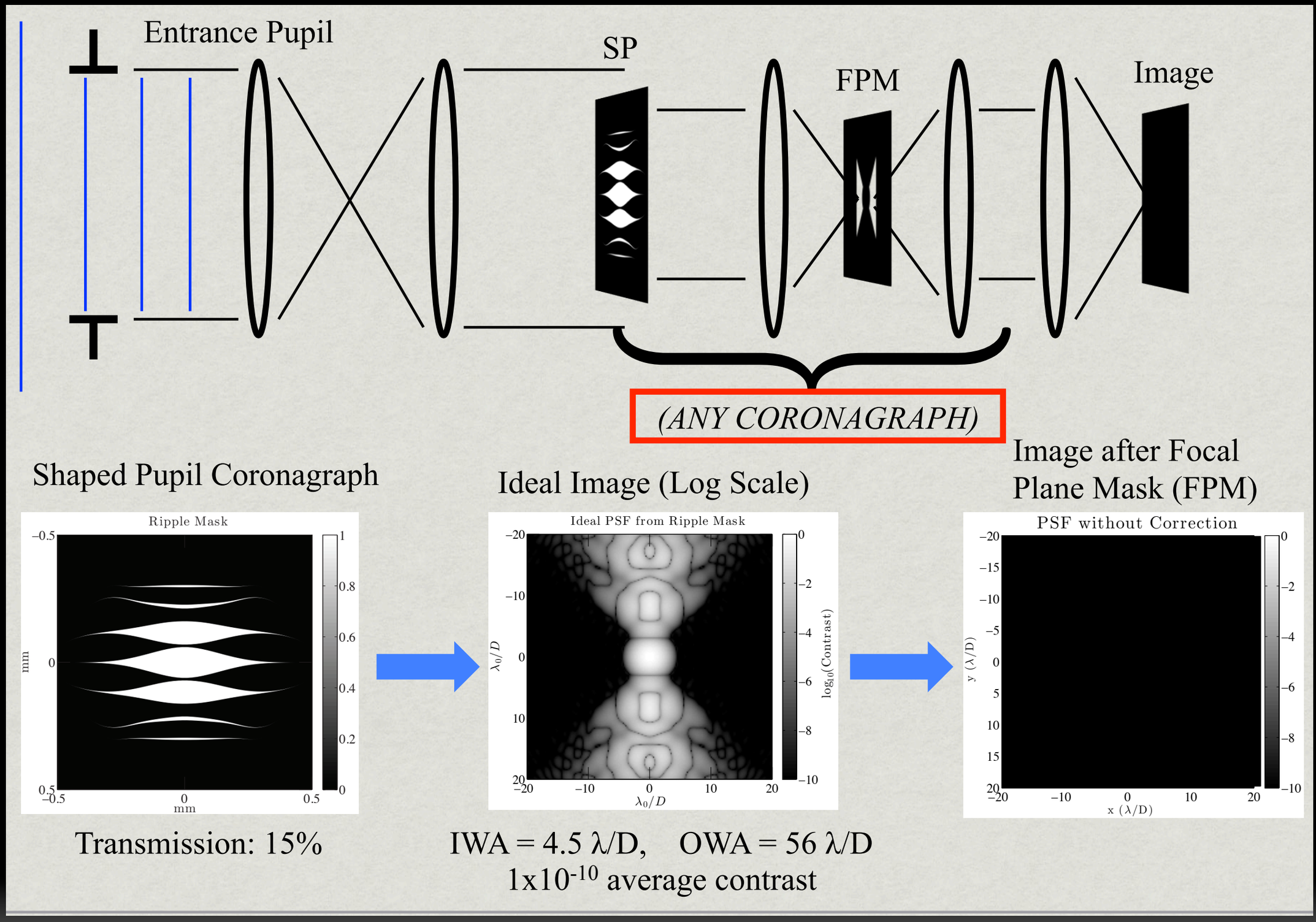
Shaped Pupil Design for AFTA

N. Jeremy Kasdin
A J Riggs, Robert Vanderbei, Tyler Groff

ACWG 2.5
October 24-25, 2013

Reminder - Shaped Pupils for High-Contrast



Transmission: 15%

IWA = 4.5 λ/D, OWA = 56 λ/D

$1x10^{-10}$ average contrast

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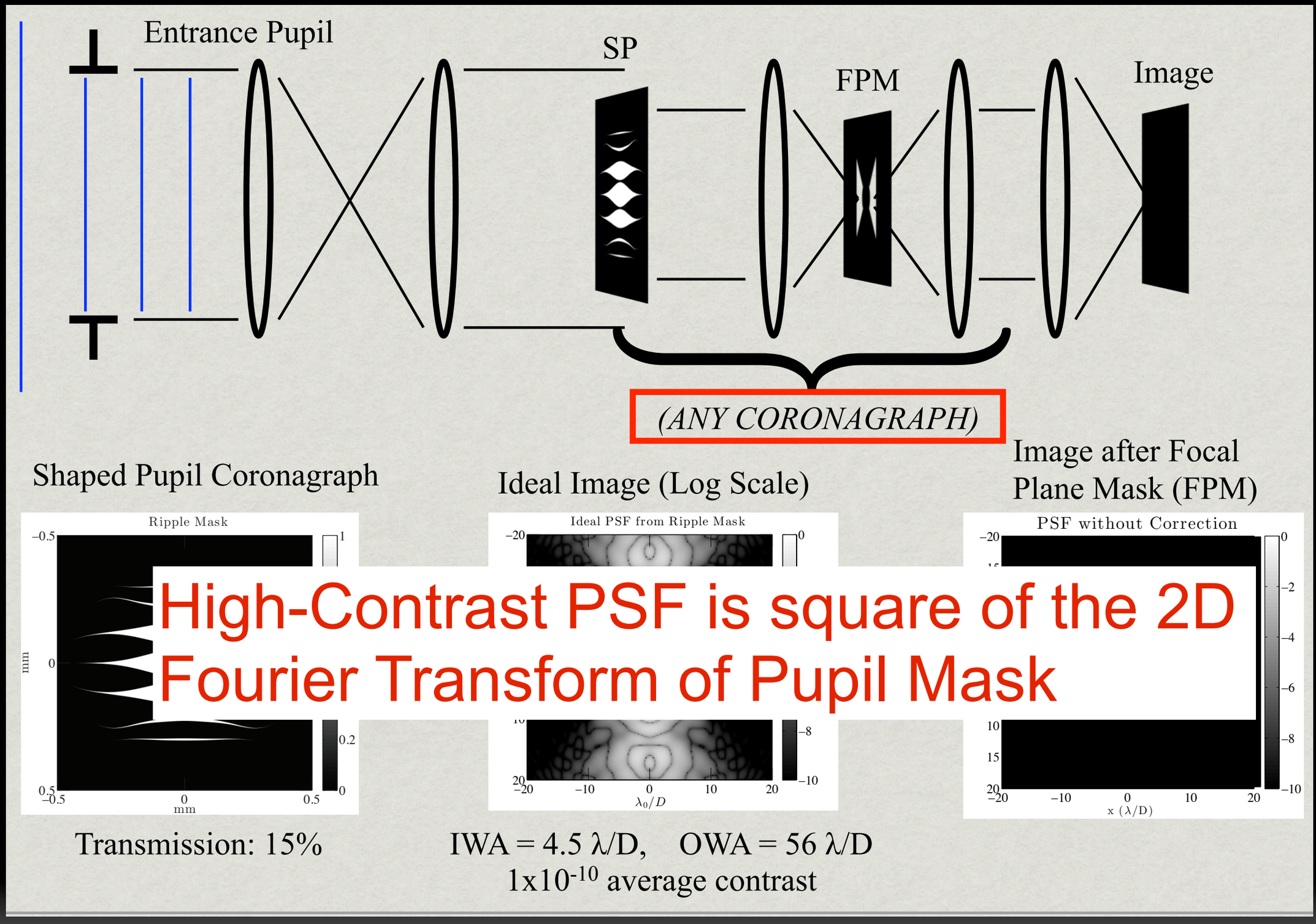

High-Contrast PSF is square of the 2D Fourier Transform of Pupil Mask

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IWA = 4.5 λ/D, OWA = 56 λ/D

$1x10^{-10}$ average contrast

Current design approach

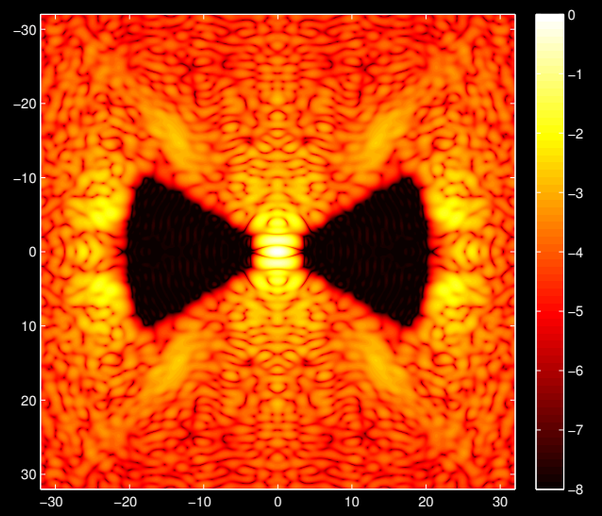
- Focus first on shaped pupil alone for high contrast.
  - Most robust and simple design
  - Achromatic (bandwidth defined by control and amplitude errors)
  - Design procedure mature and efficient
  - Minimum performance baseline
- Confirm performance in broadband
- Design multiple masks consistent with observing scenario
- Next step is high performance hybrids combined with DMs

2D optimal apodization

Shaped pupils for any aperture, achromatic.

Transmission is maximized in linear optimization problem:

$$T = \sum_{i}^{N} \sum_{j}^{N} A_{i,j} dx dy$$



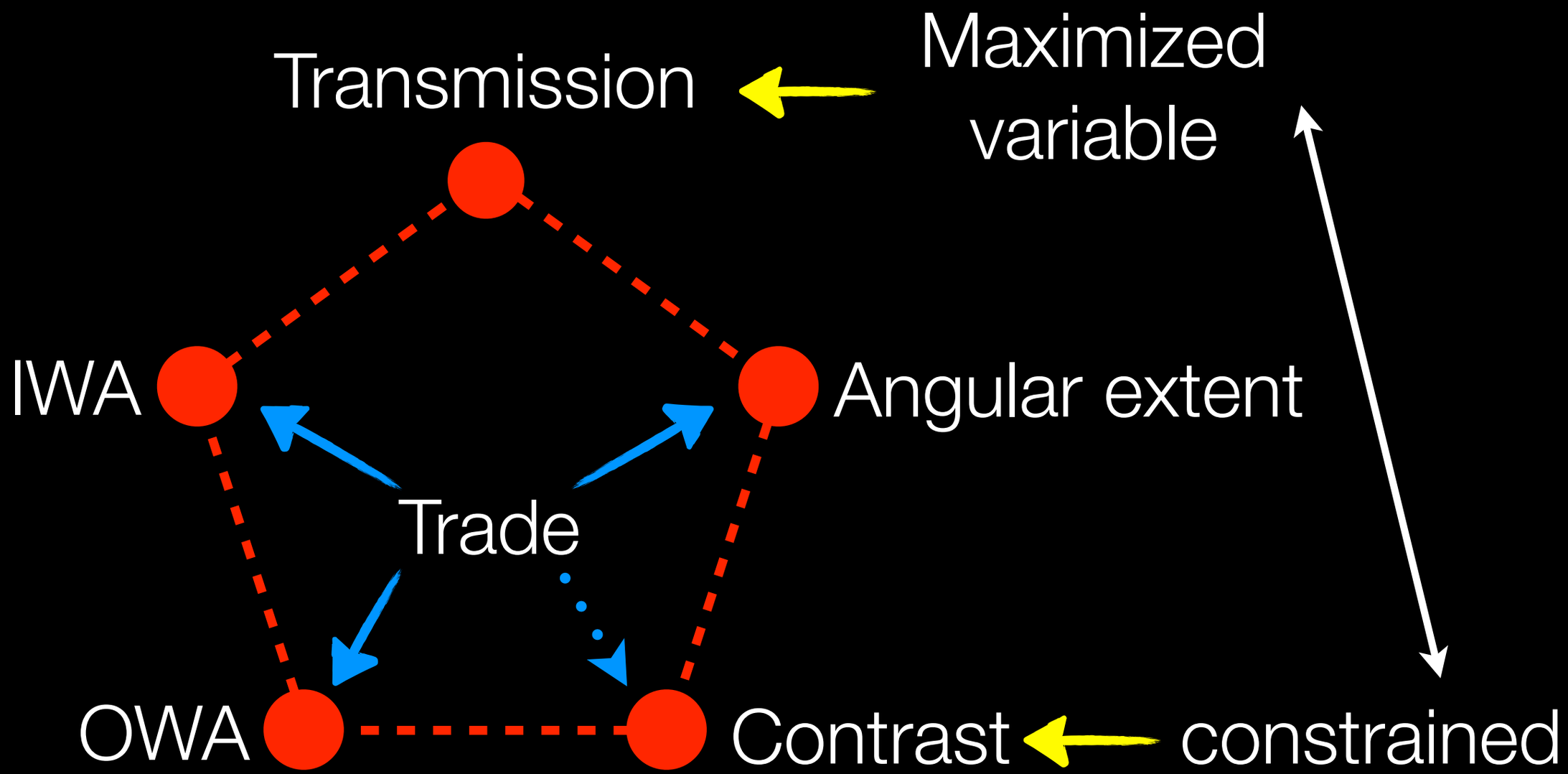
while PSF is constrained in dark holes:

$$\begin{aligned} -10^{-c/2}\widehat{F}\{A\}(0,0) &\leq \mathrm{Re}(\widehat{F}\{A\}(u,v)) \leq 10^{-c/2}\widehat{F}\{A\}(0,0) \\ -10^{-c/2}\widehat{F}\{A\}(0,0) &\leq \mathrm{Im}(\widehat{F}\{A\}(u,v)) \leq 10^{-c/2}\widehat{F}\{A\}(0,0) \end{aligned}$$

Example for AFTA: 10^{-8} from 3.6 λ/D to 20 λ/D.

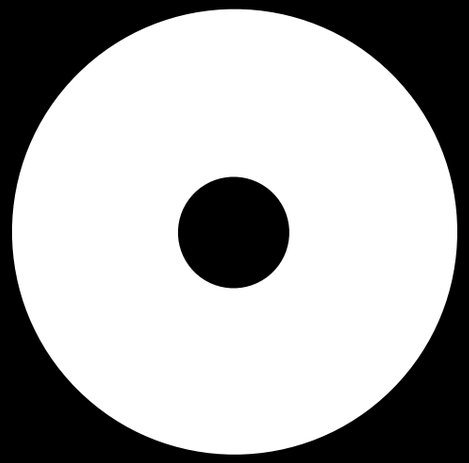
Carlotti et al. (2011); Vanderbei (2012)

Trade-offs



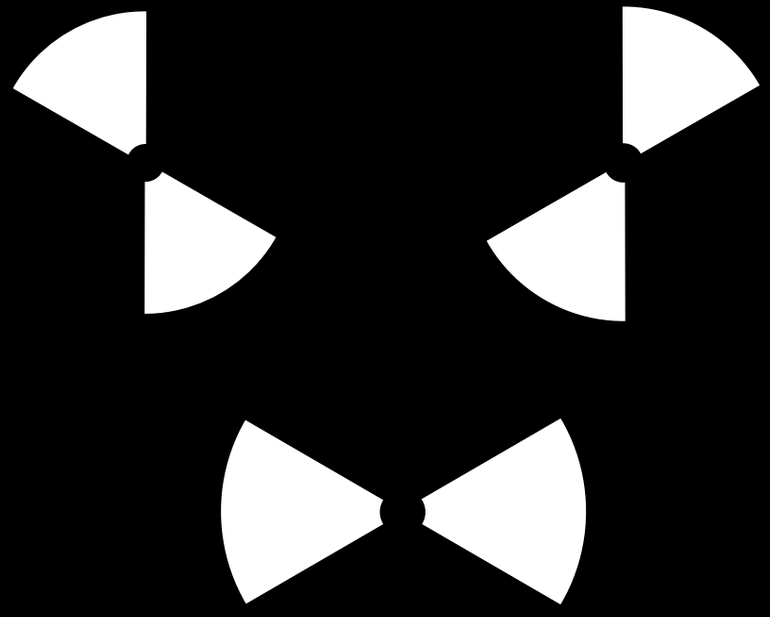
Effective throughput depends on 5 parameters

Operational Scenario



2 masks: outer & inner regions

Discovery mask with larger iwa to observe outer region over 360º at shorter wavelength.



Characterization mask(s) with smaller iwa to take spectra over broadband. Can be split into **subregions** for smaller IWA.

60 deg holes exploit 120 deg pupil symmetry, but others are possible.

diagrams not to scale

Note: some amount of telescope rotation may be required if planet falls on boundary, depending on final mask design.

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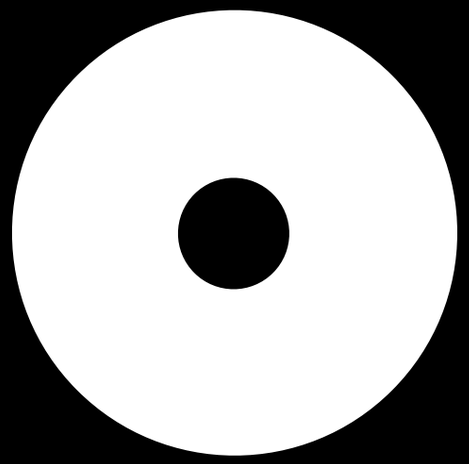

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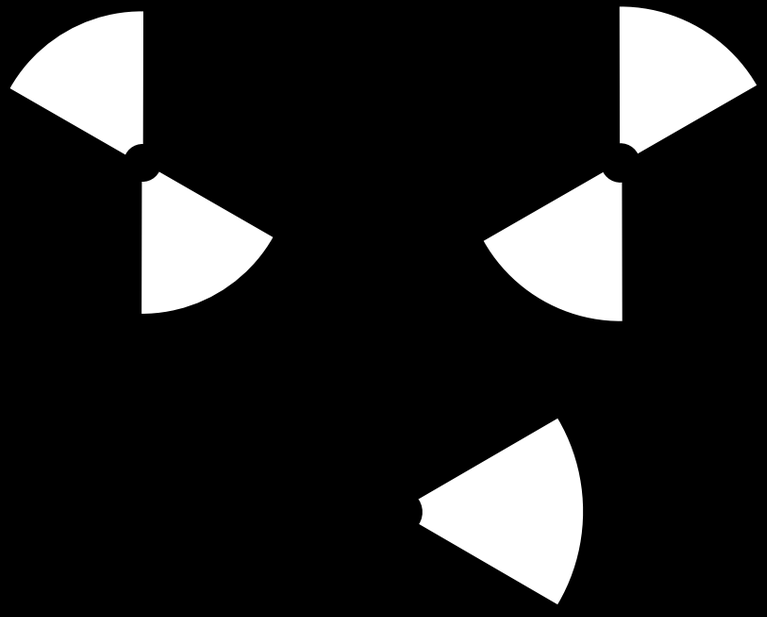

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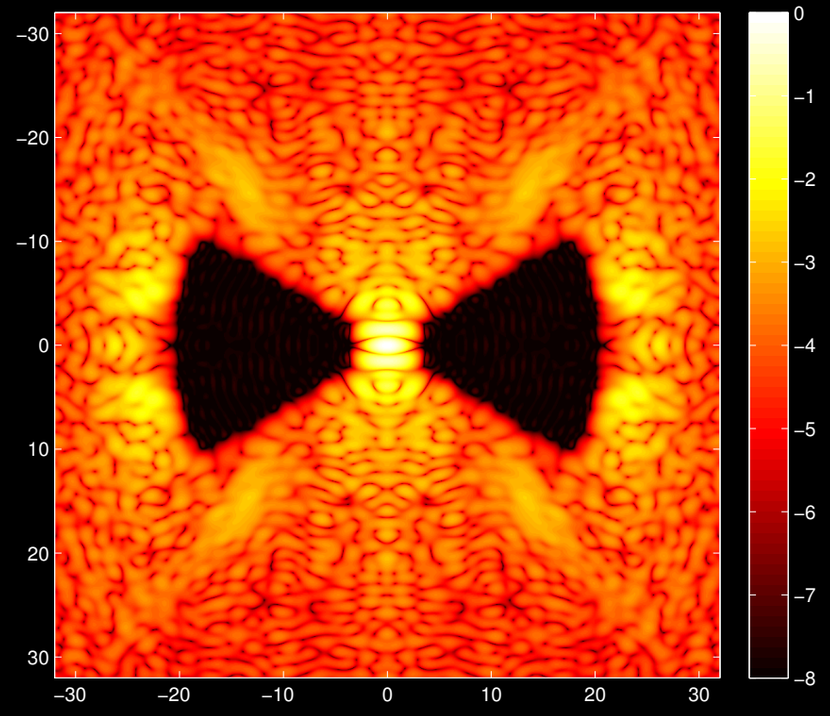
Using 3-fold symmetry



Symmetry is typically required to cover image plane without telescope rotation (using 3 masks) and speed up optimization.

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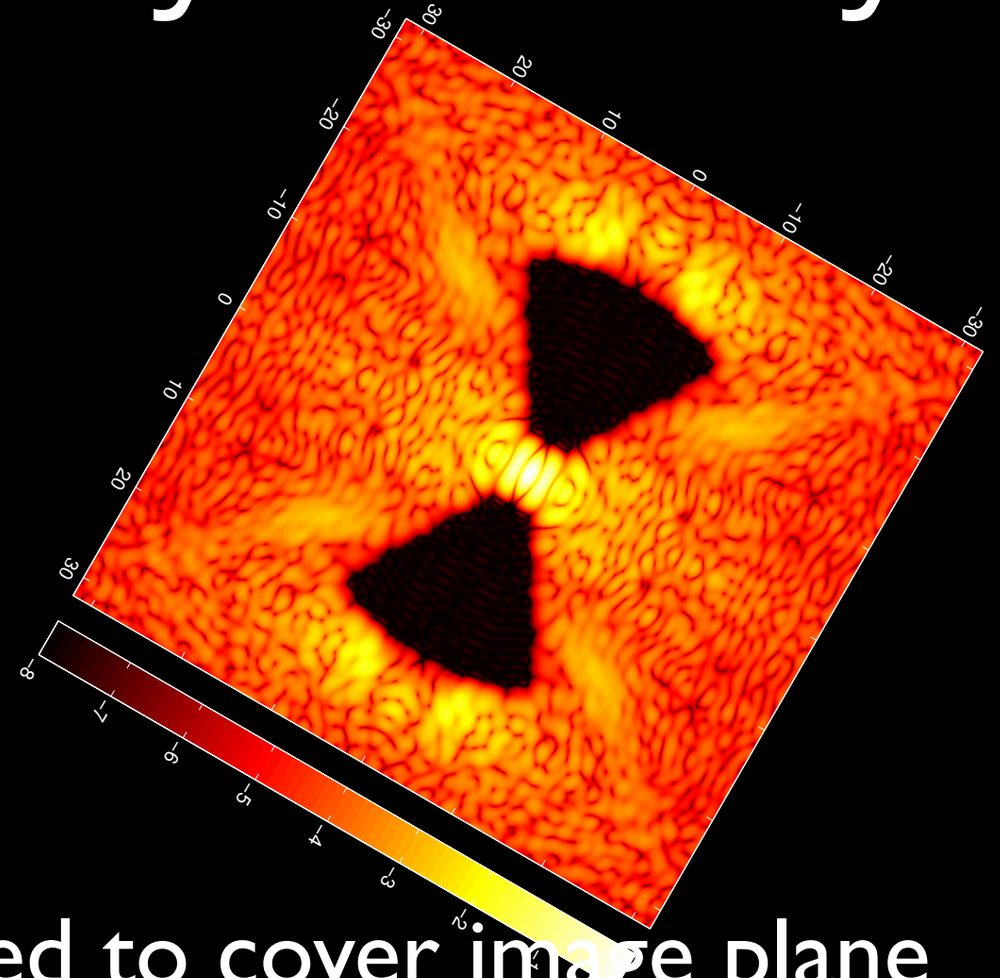

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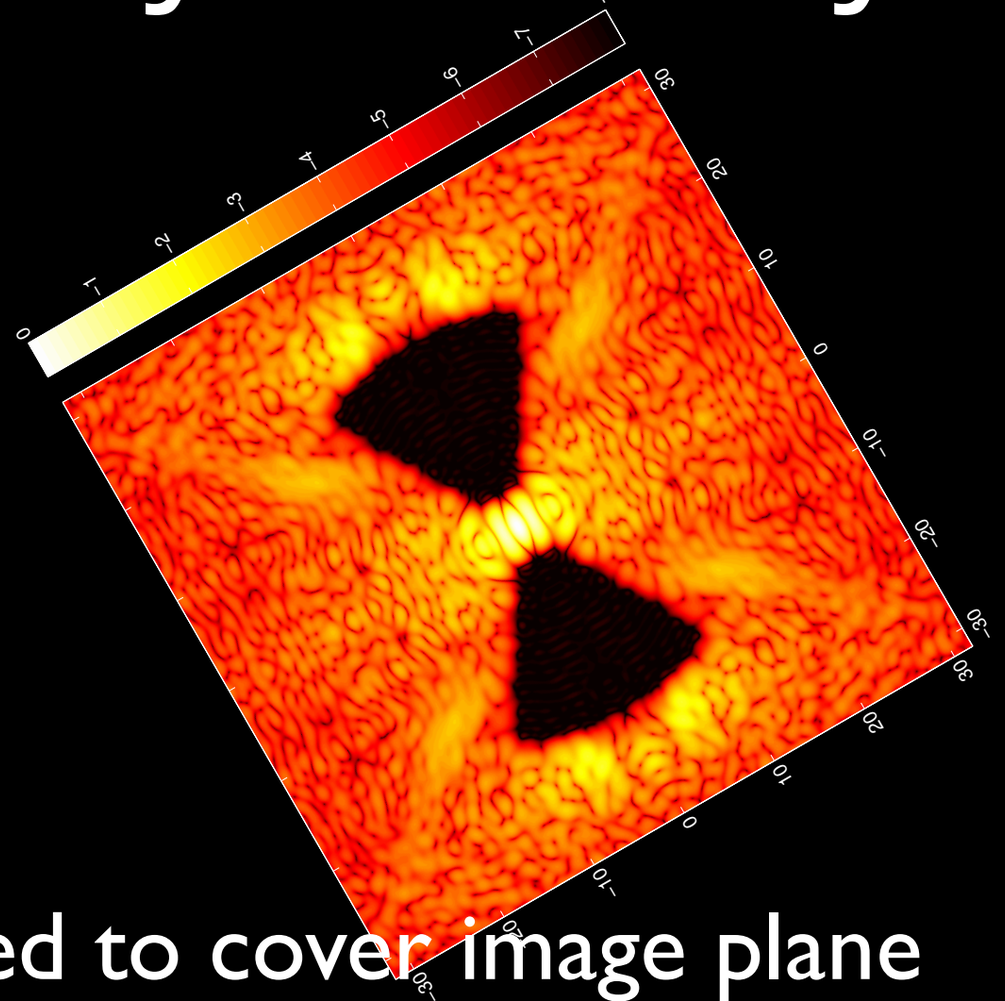

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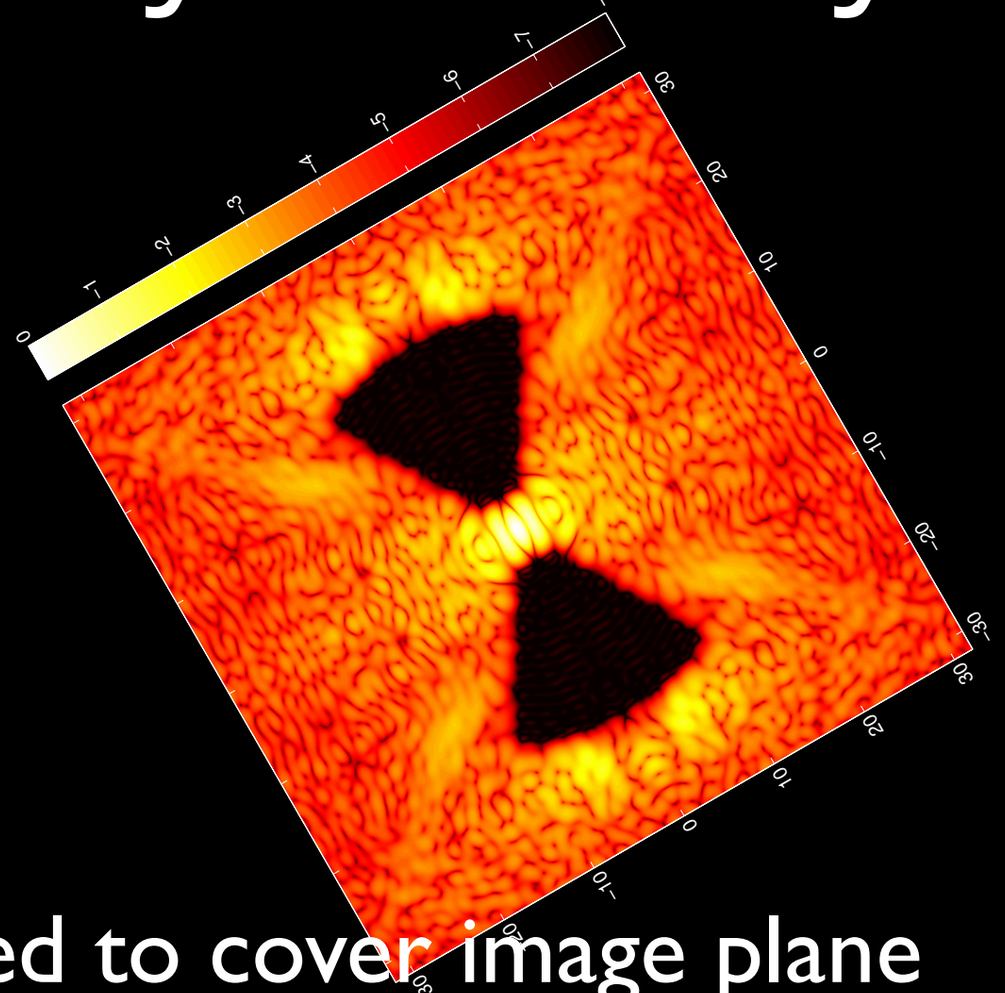


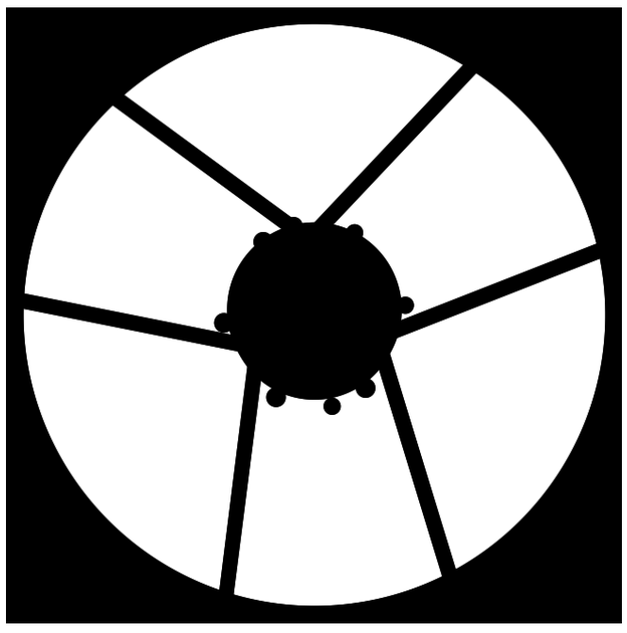
Symmetry is typically required to cover image plane without telescope rotation (using 3 masks) and speed up optimization.

We typically force symmetry through reflection or rotation. The result is a loss in throughput and iwa (spider thickness increases)

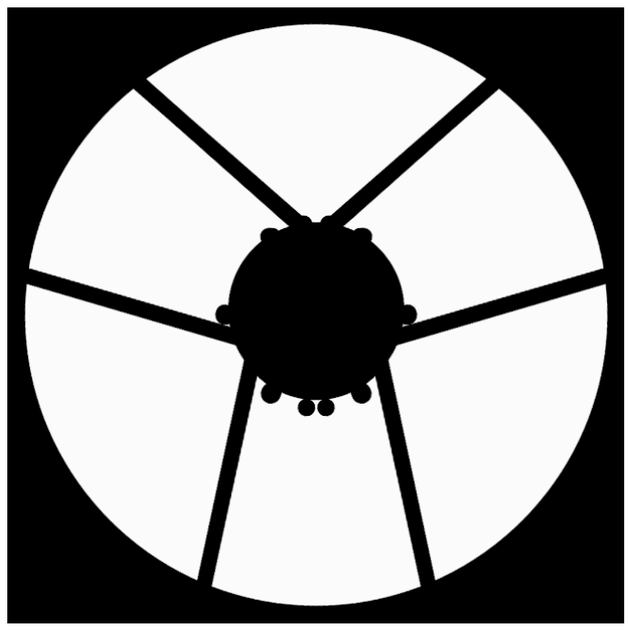
Symmetrization

- Each line of symmetry makes the optimization easier:
  - Exponential in FT reduces to: $e^{i2\pi x\xi} = \cos(2\pi x\xi)$
  - Half number of pixels in pupil and image plane
- Design for now using ¼ or ½ pupil. For final design use full or ½ pupil.

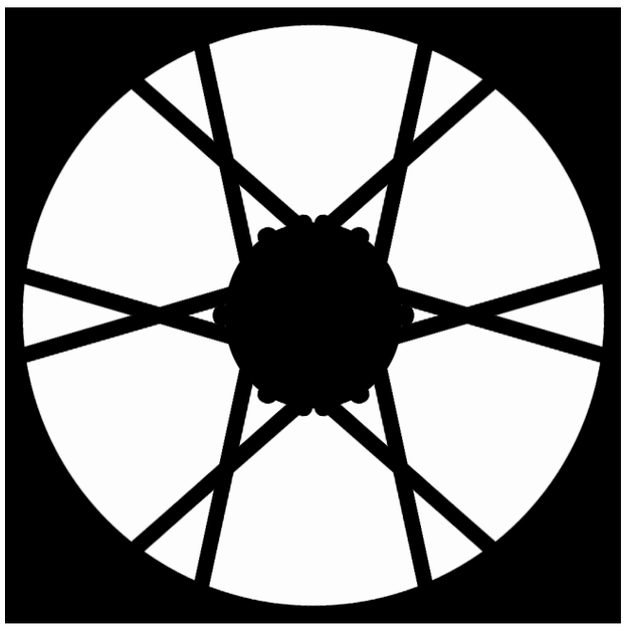
Starting pupil



Half pupil optimization



Quadrant optimization



Using single quadrant of pupil and image allows > 500x speed improvement.

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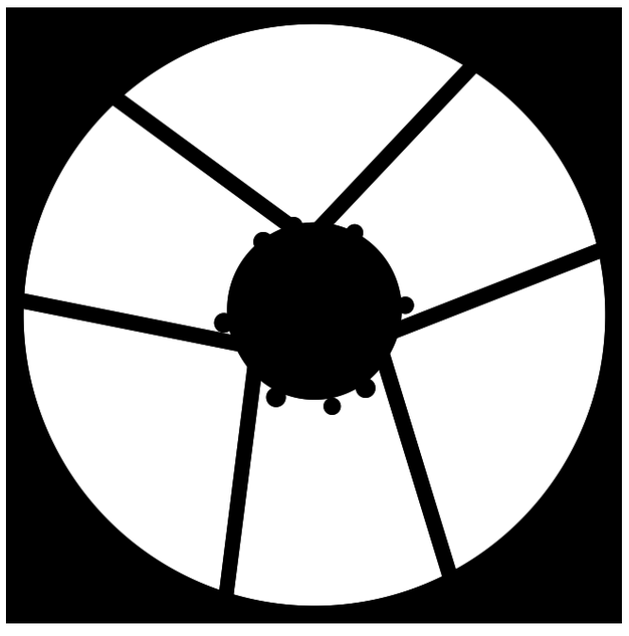

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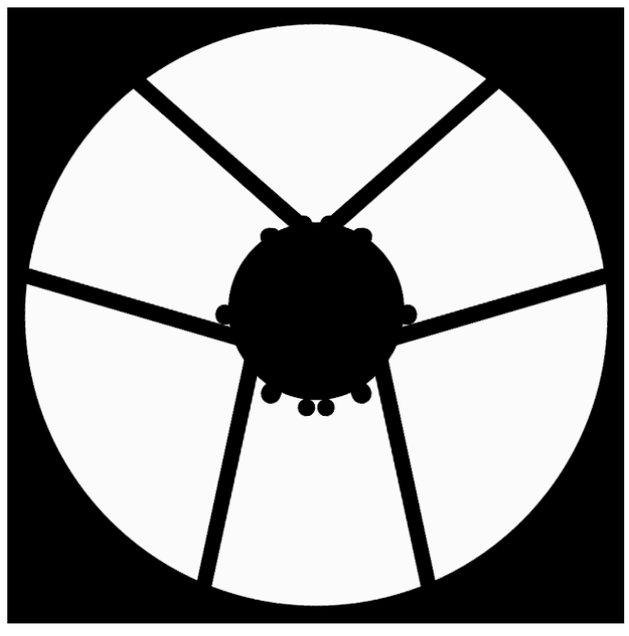

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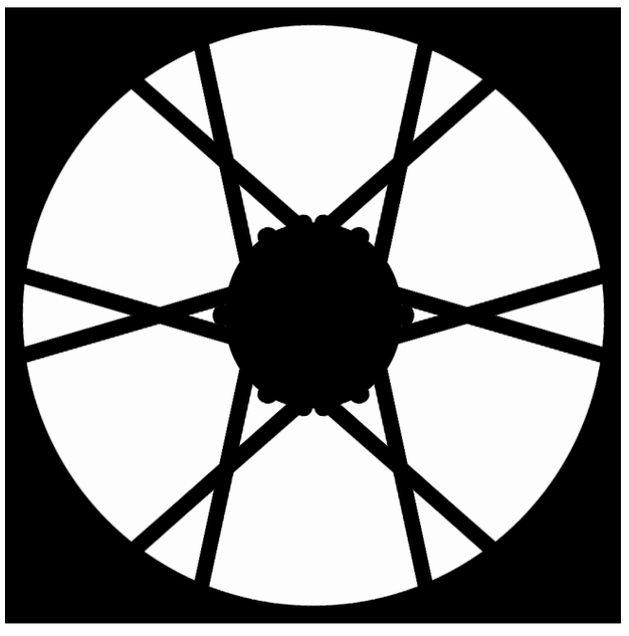
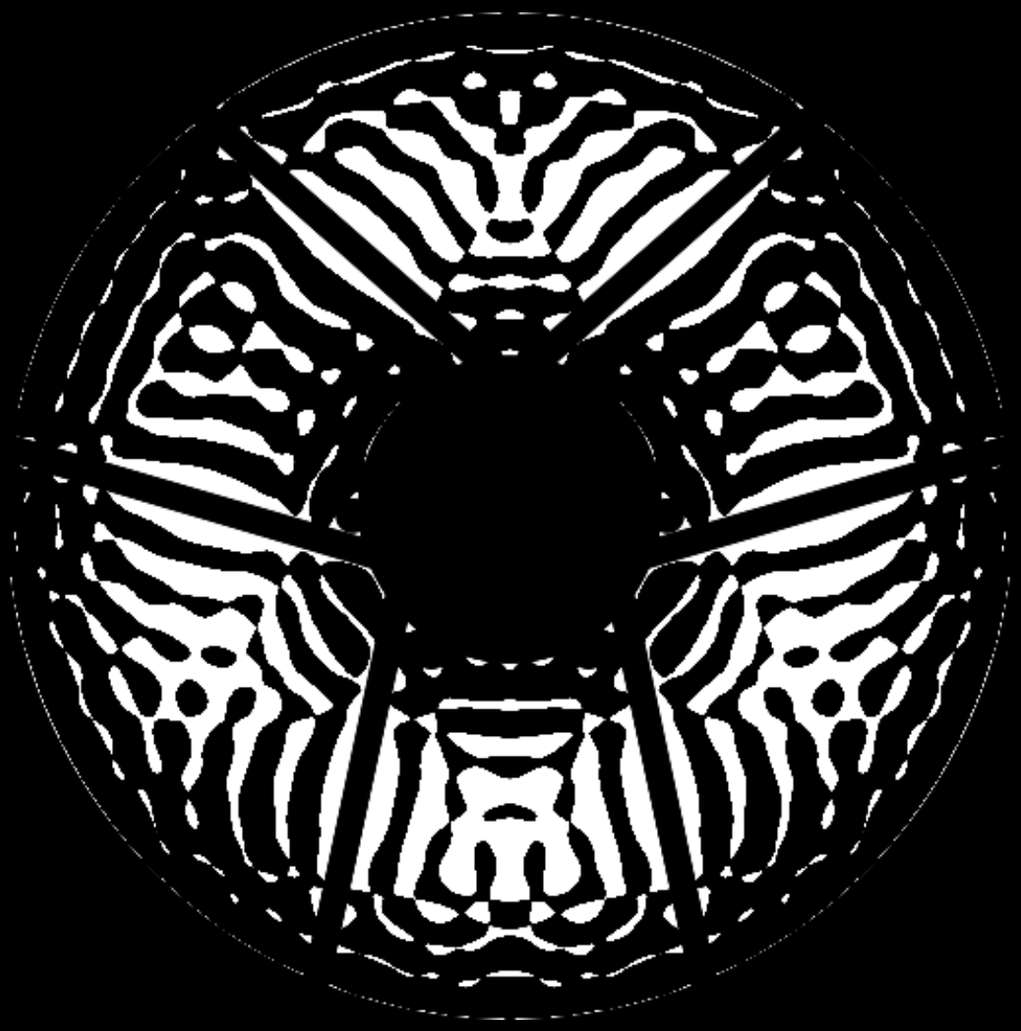


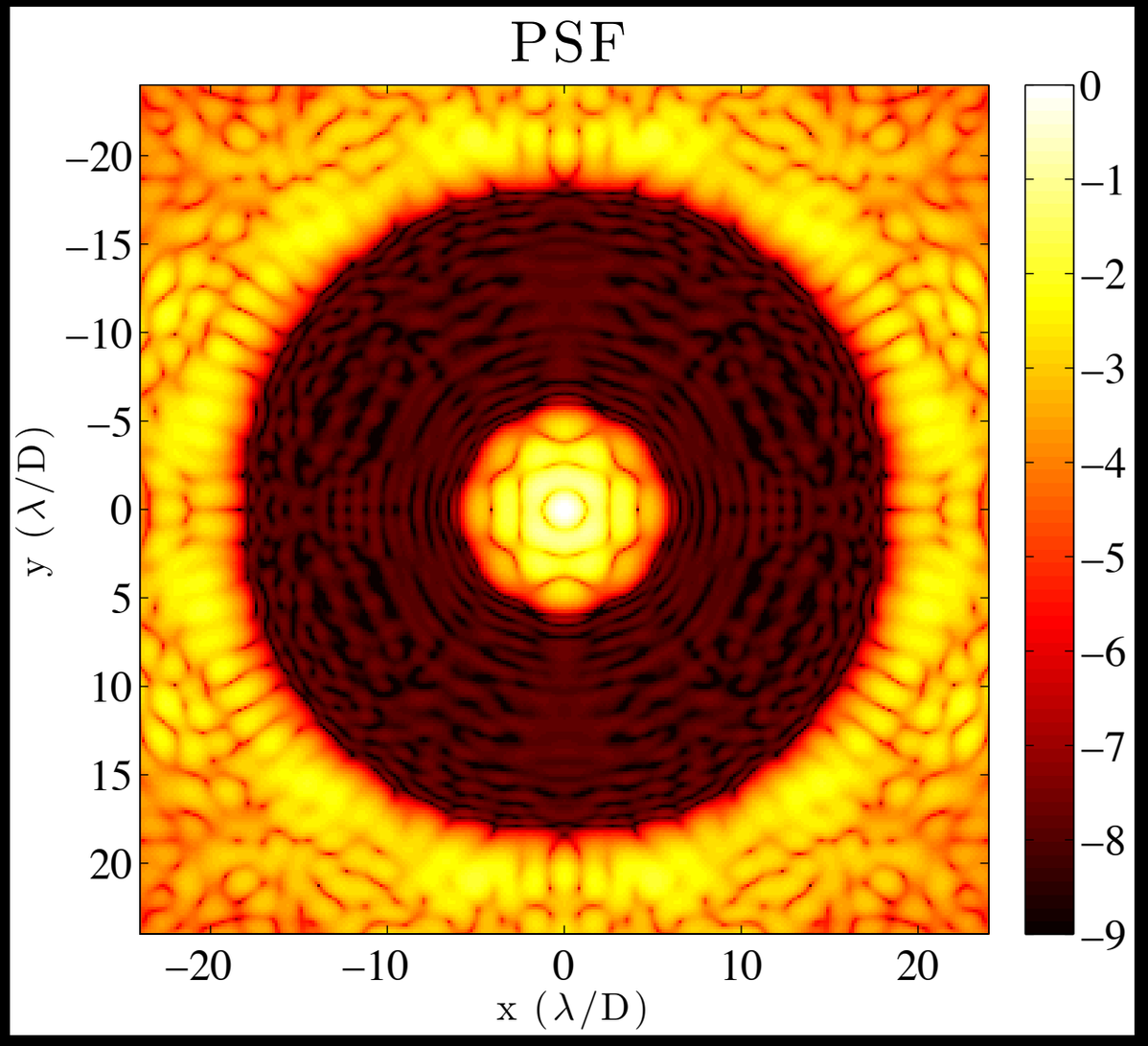
Using single quadrant of pupil and image allows > 500x speed improvement.

Pixel Count and Gray Scale

- Pixel count in John K. sims is 512 x 512
- Not sufficient to represent binary mask, so edges made "gray"
- Shaped pupil design thus left gray to best match Krist 512 x 512 pupil
- After the fact can upsample to 1000 x 1000 or more pixels and make binary. No impact on dark hole.

Discovery Mask Design

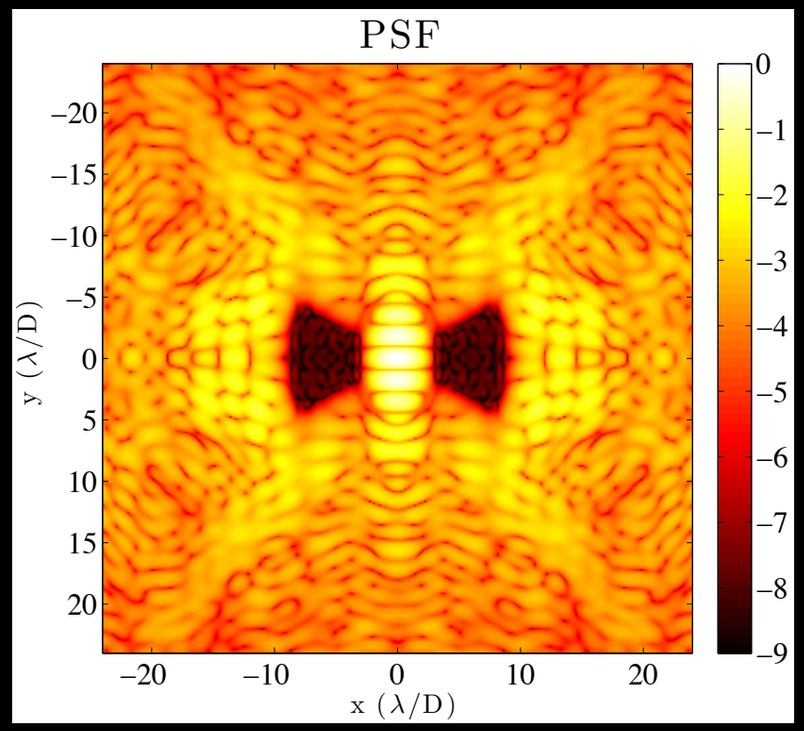




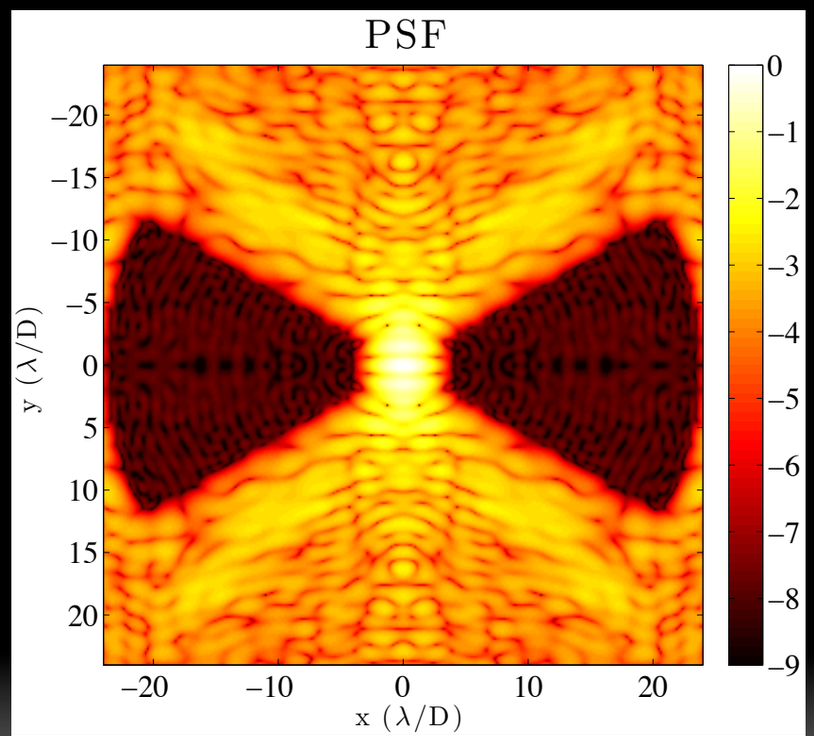
iwa: 6 lambda/D
owa: 18 lambda/D

Transmission: 29.2%
Mean Contrast: 1e-8

Characterization Mask Designs

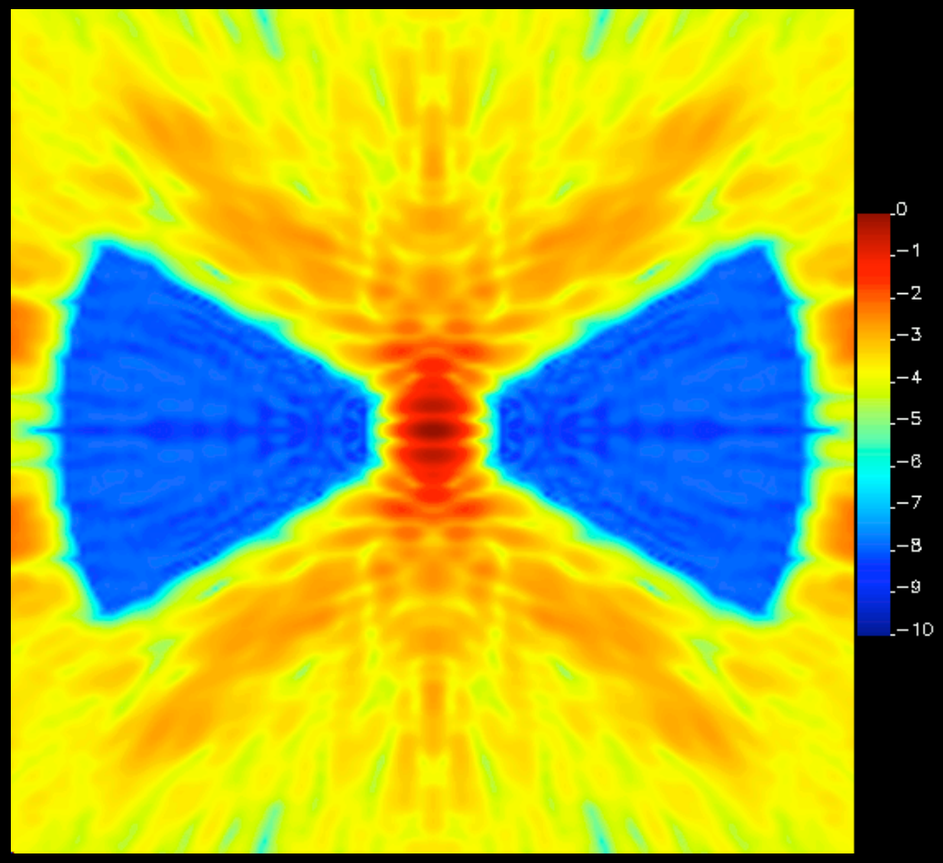


iwa: 3
owa: 9
contrast: 1e-8
Transmission: 24.4%



iwa: 3.7
owa: 23.5
contrast: 1e-8
Transmission: 22.7%

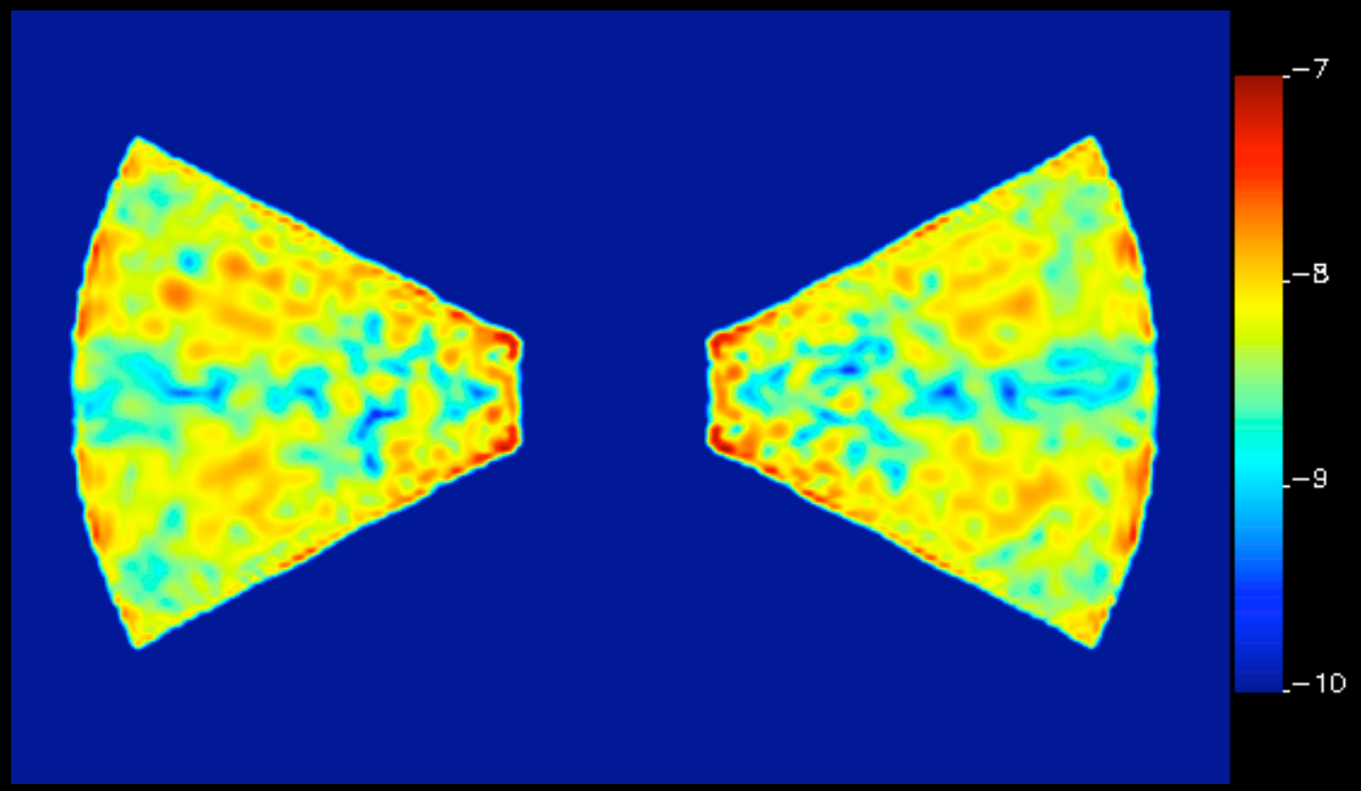
Result from John before Control (as of 10/15)

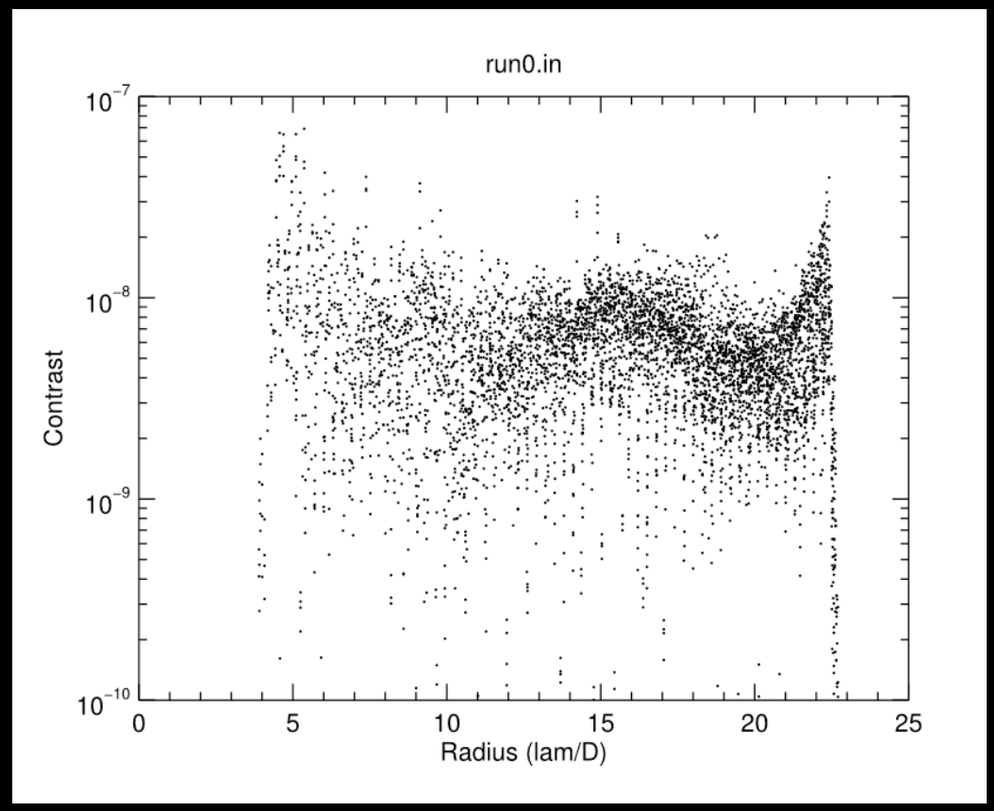


mean contrast = 1.3×10^{-8}
from 3.7 to 23.5 lambda/D

Bandpass = 522-578 nm

Result from John after Control



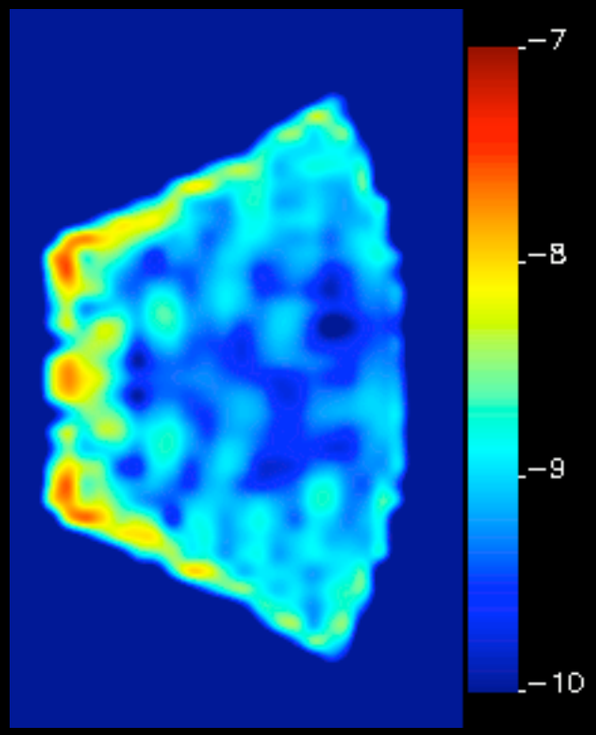


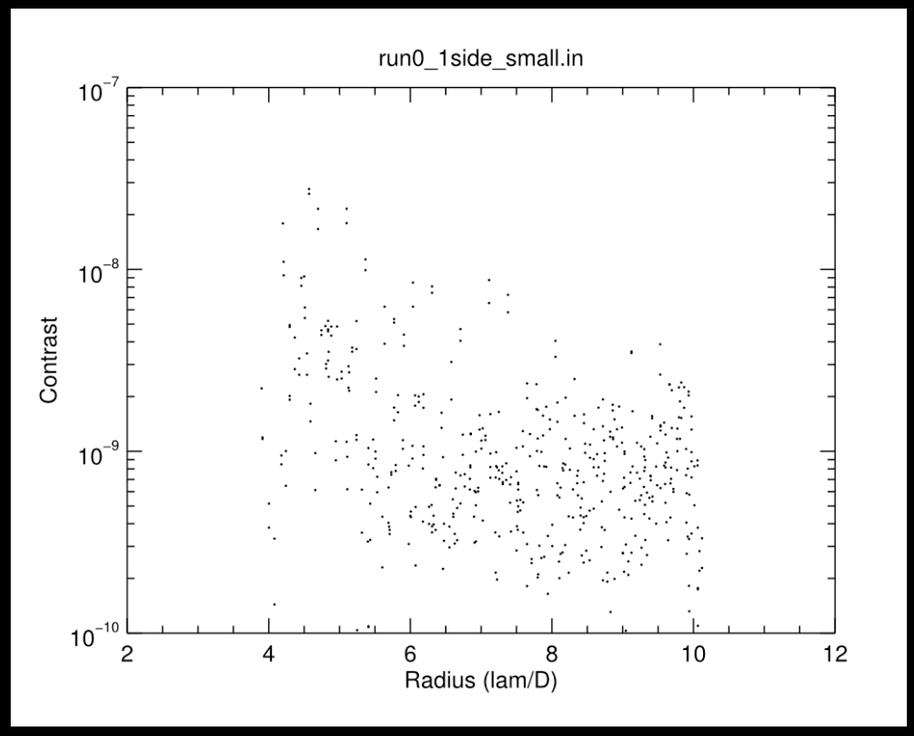
mean contrast = 6.2 x 10^{-9}
from 4 to 22.5 lambda/D

Bandpass = 522-578 nm

Result from John after Control

Smaller Dark Hole





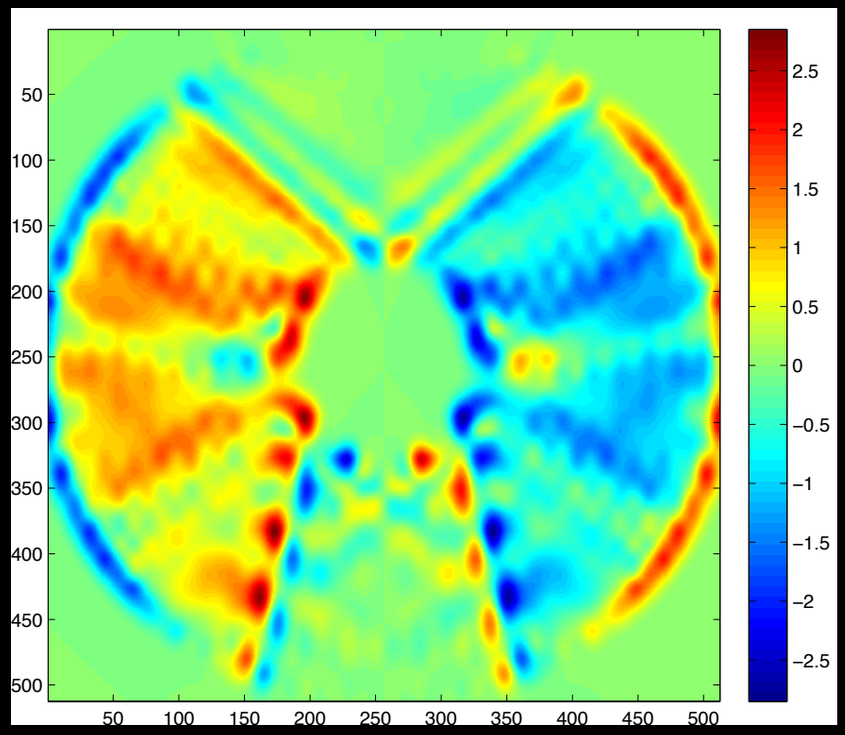
mean contrast = 1.5 x 10^{-9}
from 4 to 10 lambda/D

Bandpass = 522-578 nm

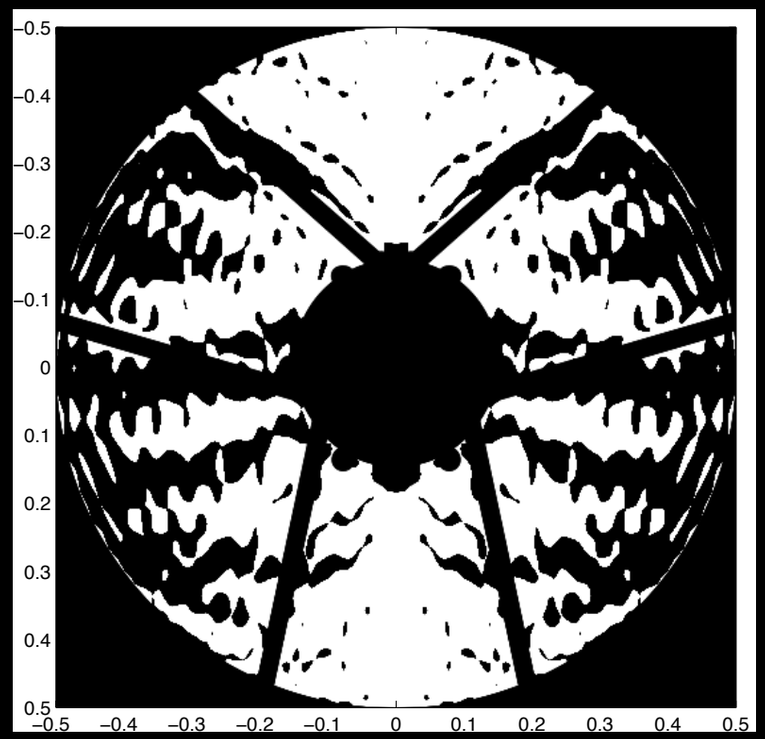
DM + SP Hybrids

- Create higher throughput and perhaps smaller iwa by combining with DM settings
- 2 DMs essentially used as pupil mappers
- Optimize directly in image plane
- Use stroke minimization to create dark hole first (at modest contrast)
- Follow with optimal shaped pupil
- Cost is likely increased chromaticity

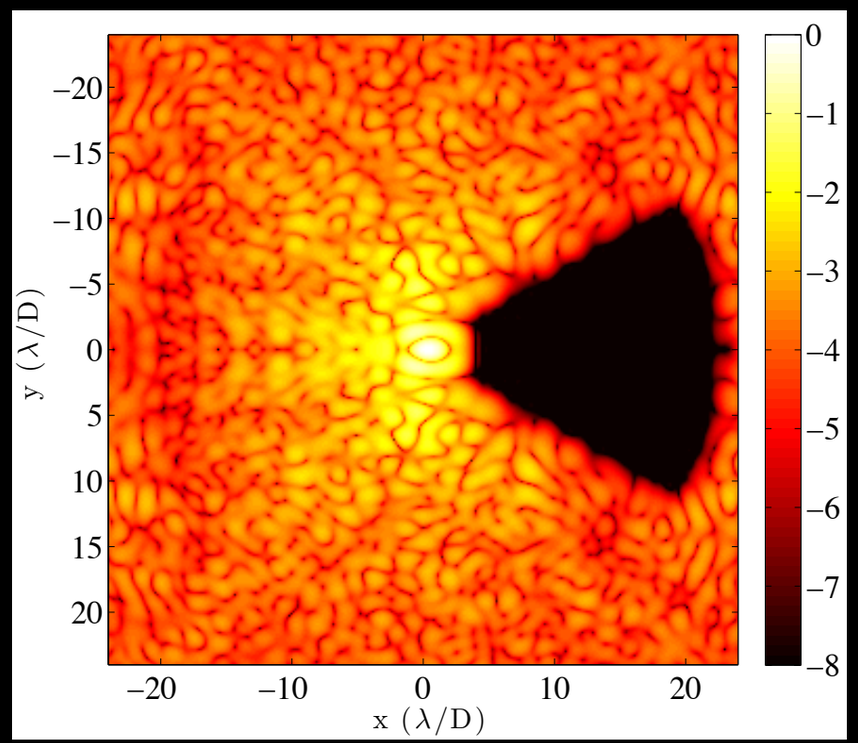
DM + SP Hybrid Solution 1



DM Setting



Shaped Pupil

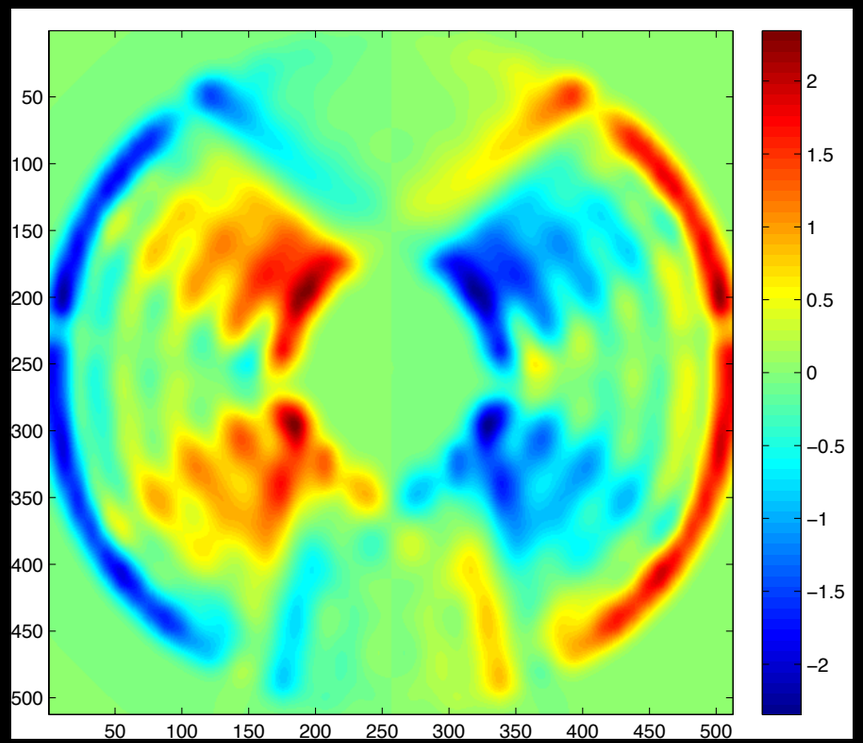


One-Sided Dark Hole

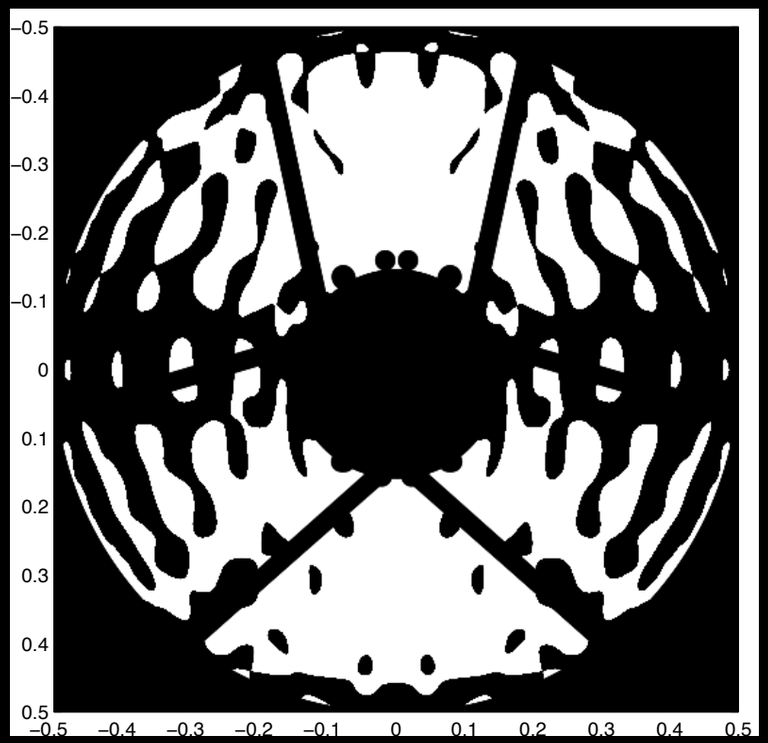
- Contrast: 5x10^{-9}
- Transmission: 61%
- Stroke: 0.91 \lambda
- IWA: 4 \lambda/D
- OWA: 22 \lambda/D

Code only in place for Single DM and one-sided dark hole. Working on 2 DM solution.

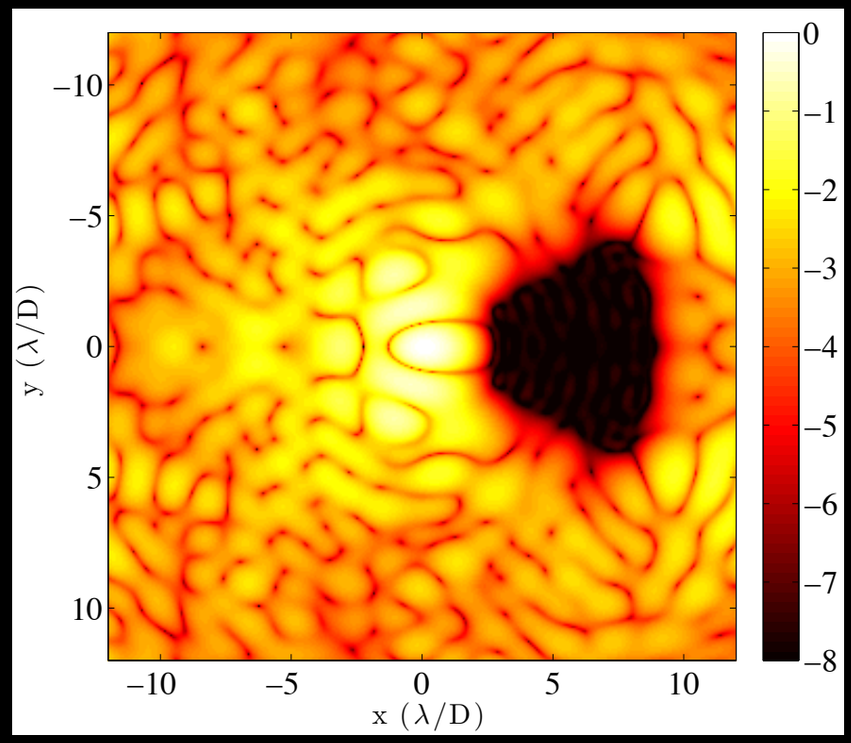
DM + SP Hybrid Solution 2



DM Setting



Shaped Pupil



One-Sided Dark Hole (different scale)

- Contrast: 1x10^{-8}
- Transmission: 57%
- Stroke: 0.75 \lambda
- IWA: 2.7 \lambda/D
- OWA: 8.8 \lambda/D

Conclusions

- Baseline design is DM+SP set to take advantage of higher transmission.
- SP only backup if baseline proves difficult in implementation or is too sensitive or chromatic.
- Designs shown here delivered to John K. on Tuesday.
- Still working on 2 DM solution/simulation, but 1 sided dark hole should be sufficient for characterization.
- This appears to be the performance limit, but still investigating other dark hole shapes.